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**Abstract**

*Lighting Answers:* Manufacturers of full-spectrum light sources have claimed a variety of benefits for their products, including better visibility, improved color rendering, better health, and greater productivity. Light sources promoted as full-spectrum can cost over ten times as much as nearly identical products that do not bear the full-spectrum claim. This report addresses questions about full-spectrum light sources: What are full-spectrum light sources? How valid are the claimed benefits? Are these products worth the extra cost? This report also proposes a convenient definition for full-spectrum light sources that can be used to quantify the extent to which a given light source deviates from a full-spectrum light source. This revision presents an improved calculation method for this new full-spectrum metric.

**Introduction**

The term full-spectrum was coined in the 1960s by photobiologist Dr. John Ott to describe electric light sources that simulate the visible and ultraviolet (UV) spectrum of natural light. There are now dozens of electric lighting products marketed as full-spectrum, some promising that they closely simulate daylight and can therefore provide benefits such as better visibility, improved health, and greater productivity. Among the claims:

- "...the closest replication of natural sunlight available." (Verilux, 2003)
- "...simulates the full-color and balanced ultraviolet spectrum of natural outdoor light." (NaturalLighting.com, 2003)
- "True daylight-balanced, full-spectrum light provides highest levels of see-ability; improves performance of color matching, close detail work and all visual tasks." (True Sun, 2003)

- "Slows aging of the retina; reduces chance of skin cancer; improves general overall mood and feeling of well-being." (Full Spectrum Solutions, 2003)
- "... perfect for plants, pets, and the treatment of seasonal affective disorder (SAD)." (Duro-Test, 2003)
- "Helps reduce eye fatigue, and are especially effective over computer screens and other visually demanding tasks." (Duro-Test, 2003)
- "Recommended for applications where high color discrimination is a must and to enhance people's sense of comfort and well being." (Lumiram, 2003)

Different companies have different ideas about what constitutes a full-spectrum light source, and what it is about full-spectrum light that yields the claimed benefits. Some insist that invisible-to-the-eye UV radiation is a necessary ingredient in full-spectrum light. Recently, several lighting products have emerged that reduce radiation in a small part of the visible spectrum in an effort to improve visibility—and these products are also called full-spectrum.

Most full-spectrum light sources are marketed at a premium price over other light sources, and they generally produce fewer lumens per watt than comparable light sources. If valid, the benefits claimed for full-spectrum light sources would seem to be well worth the additional expense and the loss in **efficacy**. But with each manufacturer making up its own definition of full-spectrum lighting, consumers have no way to know exactly what they are getting or what benefits to actually expect.

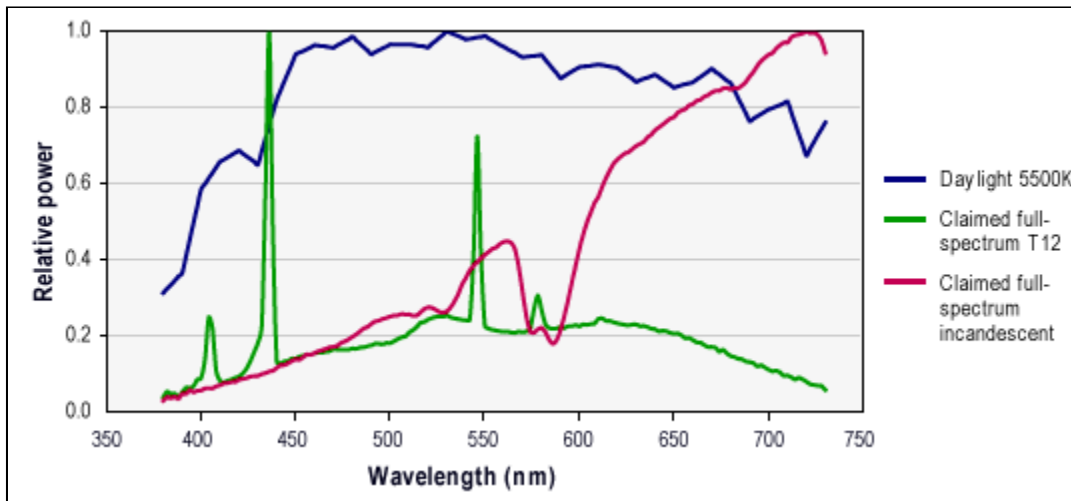
This *Lighting Answers* explores consumer perceptions about full-spectrum light sources and assesses the validity of various manufacturers' claims. This report also offers a definition of full-spectrum light sources.

### What are full-spectrum light sources?

The term full-spectrum is not a technical term, but rather a marketing term implying a smooth and continuous **spectral power distribution (SPD)** without the spikes and troughs in radiant energy common with most discharge light sources (e.g., fluorescent and metal halide). Full-spectrum products are usually marketed as electric light sources that emulate natural daylight; the explicit or implicit message is that "natural" daylight is always better than "artificial" electric light. Some full-spectrum light sources are also marketed as emitting ultraviolet (UV) radiation, as well as visible light.

Figure 1 shows the SPDs of two electric light sources claimed to be full-spectrum, the Duro-Test Vita-Lite 5500 fluorescent lamp and GE Reveal 60W incandescent lamp, as well as daylight at 5500K **correlated color temperature (CCT)**. Daylight has a smooth SPD without sharp spikes or dips, whereas the claimed full-spectrum lamps have SPDs that differ from daylight and from each other.

Figure 1. Spectral power distribution comparison



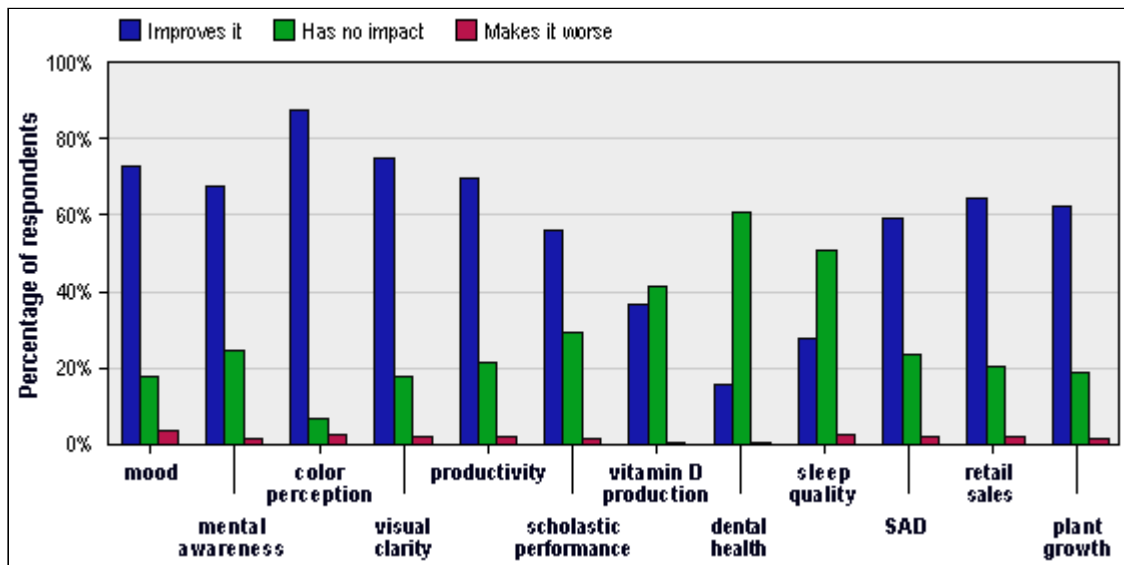
### What benefits are claimed for full-spectrum light sources?

A fluorescent or incandescent lamp claimed to be full-spectrum can cost several times as much as one with a nearly identical **spectral power distribution (SPD)** that is not identified as full-spectrum. What benefits does a consumer get for that extra money? NLP/IP reviewed the promotional claims for full-spectrum light sources from manufacturer and retailer web sites, and found a diversity of claimed benefits, including:

- Improves color perception
- Improves visual clarity
- Improves mood
- Improves productivity
- Improves mental awareness
- Improves retail sales
- Improves plant growth
- Improves results of light therapy in treating seasonal affective disorder (SAD)
- Improves results of light therapy for sleep disorders
- Improves scholastic performance of students
- Improves vitamin D synthesis in the body
- Reduces incidence of dental decay

In order to assess the impact of these manufacturer claims on the perceptions of lighting specifiers, NLP/IP conducted an online survey in April 2003. A total of 252 lighting specifiers, including electrical contractors and facility managers were asked, "Compared to other types of lighting, please indicate how you think full-spectrum light sources impact the following..." Figure 2 shows the results of the online survey.

**Figure 2. Perceived benefits of full-spectrum light sources among lighting specifiers**



Because some participants did not respond to all survey questions, the responses for each perceived benefit may not add up to 100%.

Overall, the survey respondents believed in most of the claimed benefits of full-spectrum light sources. For nine of the twelve potential benefits, more than 50 percent of the respondents believed that full-spectrum light sources have a positive effect. More people believed in a positive effect on color perception than any of the other potential benefits, with 86 percent responding positively. The least believed claim was improved dental health, with only 15 percent responding that full-spectrum light sources affected it positively. For all claimed benefits, less than 4 percent of the respondents believed that full-spectrum light sources actually had a negative impact.

As registrants of NLPPIP's web site, the audience that participated in this survey probably has lighting technical knowledge greater than that of the average person, but similar to that of the typical lighting specifier. The results of this survey indicate that the marketing message from manufacturers of full-spectrum light sources appears to be getting through to its intended audience of lighting specifiers.

### How valid are the claims regarding full-spectrum light sources?

**Full-spectrum light sources and color perception.** Full-spectrum light sources will probably provide excellent color rendering. **Color rendering index (CRI)** values for full-spectrum lighting sources are typically greater than 90. Color is a human perception constructed from the combination of the **spectral power distribution (SPD)** of the light source, the spectral reflectance of the materials being illuminated, and the tri-chromatic nature of the human visual system. If there are gaps or large variations in the SPD of a light source, there is a potential for confusion between the apparent colors of objects. Since full-spectrum light sources usually provide radiant power throughout the visible spectrum, subtle differences in the spectral reflectance characteristics of different objects are discernable. So, when color identification is part of the visual task, such as for graphic arts, museums and color printing applications, full-spectrum light sources will ensure good color discrimination.

**Full-spectrum light sources and visual performance.** Full-spectrum light sources will not provide better visual performance than other light sources under most circumstances. Visual performance is the speed and accuracy of processing achromatic information (e.g., black print on white paper) by the human visual system. At the relatively high light levels typically found in schools and offices, visual performance is essentially unaffected by the spectral power distribution of the light source, so full-spectrum light sources are, lumen for lumen, no better than any other light source.

Lighting produced by full-spectrum lamps may be, however, perceived as providing brighter architectural spaces than other lamps (Boyce, 2002; Berman, 1990). Three factors may contribute to this effect. First, full-spectrum light sources typically have a high **correlated color temperature (CCT)** of 5000K - 7500K. Lamps with higher CCT values produce greater brightness perception than lamps with lower CCT of the same luminance. Second, most

full-spectrum light sources have high color rendering properties, meaning that surface colors will appear more saturated. Greater saturation will also give the impression of greater brightness (Boyce, 1977). Third, the ultraviolet (UV) radiation produced by some full-spectrum fluorescent lamps has a fluorescing, brightening effect on textiles and paper that have been treated with whitening agents. These combined effects on brightness perception may indeed have positive impact on building occupants, but greater perceived brightness can also be a liability, depending upon the expectations of the space's occupants (Veitch and McColl, 2001).

**Full-spectrum light sources and health.** Full-spectrum light sources will not provide better health than most other electric light sources. Recent research has shown that human daily activities are strongly influenced by the solar light/dark cycle. The most notable of these daily, or circadian, cycles is the sleep/wake cycle; but other activities including mental awareness, mood, and perhaps even the effectiveness of the immune system go through regular daily patterns. Light is the most important environmental stimulus for regulating these circadian cycles and synchronizing them to the solar day. Short wavelength (blue) light is particularly effective at regulating the circadian system; long wavelength (red) light is apparently inconsequential to the circadian system. Thus, to maximize efficiency in affecting the circadian system, a light source should not mimic a full spectrum, but instead should maximize only short wavelengths. Even if a full-spectrum light source includes short wavelength light in its spectrum, it will not necessarily ensure proper circadian regulation because, in addition, the proper intensity, timing, and duration of the light exposure are all equally important for satisfactory circadian regulation (Rea et. al, 2002).

Light therapy treatment of seasonal affective disorder (SAD) usually involves regulated exposure to a white light source, commonly 10,000 lux at the eye for 30 minutes per day (Partonen and Lönnqvist, 1998). Any white light source will be effective at these levels (Lam and Levitt, 1999), so full-spectrum light source is in no way special for treatment of SAD.


Full-spectrum light sources have no demonstrable benefit for dental health. These claims have no scientific merit (McColl and Veitch, 2001). The section, "Is ultraviolet radiation production important?" gives more detail.

**Full-spectrum light sources and psychological benefits.** Full-spectrum light sources may have psychological benefits, particularly in societies that place value on "natural" environments. One of the claims often associated with full-spectrum light sources is that they are most like natural daylight. Unlike full-spectrum electric light sources, however, daylight does not have a fixed spectrum. Rather, natural light varies with latitude, time of day, season, cloud cover, air pollution, ground reflectance, and, if a person is indoors, window tinting. Nevertheless, it cannot be denied that people consistently prefer natural lighting from windows and skylights to electrical lights. These preferences are robust and may reflect psychological associations with the natural environment that produce **positive affect** in many people. Positive affect induced by daylight may, in fact, help improve mood and motivation and thus increase productivity and retail sales. Full-spectrum light sources offer this positive association with daylight. Although positive psychological benefits from full-spectrum light sources may have been observed in some circumstances, there appears to be no biophysical explanation for those observations (Heschong, Wright & Okura, 2000). Still, the power of psychological associations cannot be denied and it is certainly conceivable that cleverly marketed full-spectrum light sources may provide beneficial effects to some people susceptible to that marketing. As NLPIP's survey demonstrated, there appears to be a strong positive association with full-spectrum light sources that has resulted from marketing, presumably because of the association between full-spectrum lighting and "natural" light.

## Is ultraviolet radiation production important?

Some full-spectrum fluorescent lamps are promoted as producing ultraviolet (UV) radiation. This is peculiar, since in general, UV radiation should be avoided. UV radiation fades and deteriorates architectural materials and works of art. Even though full-spectrum lamps might improve the color appearance of artwork, museums specifically require all radiation shorter than 400 nm to be filtered completely from light sources illuminating environmentally sensitive pieces, such as watercolor paintings, and historical artifacts (Rea, 2000). Except in certain unusual cases, it is also undesirable for people to expose the eye or the skin to UV radiation. Adverse effects of excessive UV radiation include sunburn (erythema), cataracts, and skin cancer (Rea, 2000). Several organizations, including the Illuminating Engineering Society of North America (IESNA), the American Conference of Governmental Industrial Hygienists (ACGIH), and the National Institute for Occupational Safety and Health (NIOSH), have specified acceptable limits for occupational ultraviolet exposure (IESNA, 1996; ACGIH, 1991; NIOSH, 1972).

However, skin exposure to a fairly narrow band of UV radiation, UVB between 290 and 315 nm, can promote the synthesis of vitamin D, which is necessary for proper bone development and maintenance (Holick, 1985). Dietary sources of vitamin D, including dairy and fish products, provide sufficient vitamin D to have eliminated the incidence of bone-related problems such as rickets, in modern society (Jablonski and Chaplin, 2002.). These dietary supplements therefore minimize the importance of UVB radiation exposure for most people.

Full-spectrum fluorescent lamps that produce UV radiation use special phosphors with peak emissions in the UVA band (315 nm-400 nm), typically at 355 nm. Although the relative amount of UV radiation emitted by these lamps may be the same as a particular phase of daylight, the absolute amount of UV radiation they emit is quite small. For comparison, approximately 22 minutes of sunlight exposure near midday will produce 1.5 **minimal erythema doses (MEDs)** of UVB radiation exposure, enough to induce a pronounced temporary increase in vitamin D concentration (Holick, 1985). One MED is the amount of exposure that produces noticeable skin redness, so the exposure needed to affect vitamin D levels is substantial. Based upon the published data from one manufacturer of fluorescent lamps emulating the UVB content of daylight, it would take at least 30 hours of constant exposure to these lamps when operated at ceiling height to provide 1.5 MEDs (see the [CASE STUDY](#) ). Based on UVB intensity data from another study (Ball, 2002), eight hours in an office or classroom under a claimed full-spectrum lamp will produce a smaller ultraviolet dose than one minute spent outdoors in bright sunlight.

Indoor environments such as offices and schools further reduce UV exposure because most lighting fixtures and architectural materials absorb UV radiation. UVB radiation that does not strike the skin directly is unlikely to reflect off objects, floors, and walls back to the skin. The resulting exposure level will be well below the threshold for measurable vitamin D production. Therefore, fluorescent lamps claiming to emulate the relative UV content in daylight can be disregarded as a viable source of UVB radiation for humans. Since there are no known benefits to human health from UVA radiation, it can be further concluded that the modest amounts of UV radiation produced by these lamps have no beneficial impact on human health.

Ironically, even small but constant amounts of UV (UVA and UVB) radiation will eventually degrade a wide variety of architectural materials such as carpet and cloth, wood products, and printed matter.

One claim occasionally cited as a benefit of fluorescent light sources emulating the UV content of daylight is the enhanced brightness of paper and clothing treated with whitening agents. Fluorescent whitening agents are used to counteract the otherwise yellow appearance of paper and cloth, making them appear whiter and brighter.

To assess this claim, NLP/IP compared the relative luminance of white paper and of white cloth illuminated alternately by two fluorescent lamps of identical **correlated color temperature (CCT)**, one claiming to emulate the relative UV content of daylight and one without the UV phosphor. By causing the whitening in the cloth or paper to fluoresce, the UV radiation from these lamps should produce higher luminance for the same given illuminance. Indeed, the measured luminance of a white paper sample and of a white cloth sample were 1.7% and 2.3% higher, respectively, when illuminated by the full-spectrum fluorescent lamp with more UV radiation.

These effects were also perceptible when alternatively viewed, but any assumed benefits of these relatively small brightness-enhancing effects have never been documented. It should also be noted that lamps emulating the UV content of daylight have about 30% to 40% lower lamp **efficacy** (lumens per watt) than conventional fluorescent lamps of the same CCT, partly because additional electric power is required to generate the invisible UV radiation.

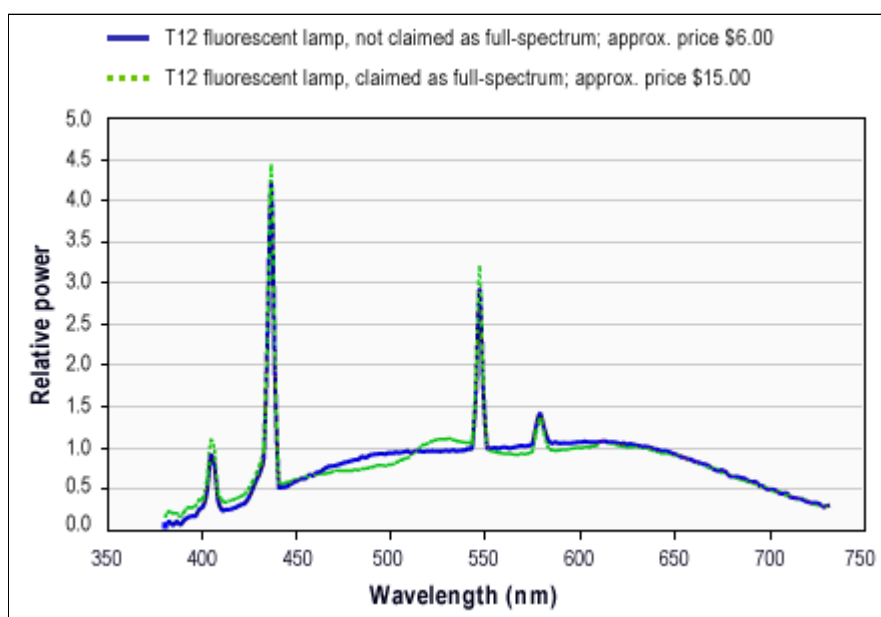
In summary, there are no known health effects from the UV radiation generated from these lamps, but the UV radiation from these lamps can be harmful to many of the materials commonly found in architectural spaces. Further, although the UV radiation generated from these lamps can induce relatively higher luminance in white paper and clothing, the loss in lamp efficacy needed to produce the invisible UV radiation is substantially greater than the fluorescence-induced luminance resulting from UV radiation.

### What are the disadvantages of full-spectrum light sources?

Other than potential damaging effects on architectural materials from full-spectrum light sources that produce ultraviolet (UV) radiation, the primary disadvantages of full-spectrum lamps are economic. Full-spectrum lamps are often priced several times higher than conventional lamps. For example, in Troy, New York, a four-foot T12 lamp costs between \$1.25 and \$3.60, while a full-spectrum four-foot T12 lamp costs \$14.90.

In comparing **spectral power distributions (SPDs)** for this report, NLPPI found that one of the major lamp manufacturers offers a \$5.86 four-foot T12 fluorescent lamp with a spectrum nearly identical to that of the \$14.90 full-spectrum lamp, but the manufacturer of the less expensive lamp does not market it as a full-spectrum lamp. Figure 3 compares the spectra of the full-spectrum lamp costing \$14.90 and the \$5.86 lamp.

**Figure 3. Spectral comparison of a claimed full-spectrum lamp and a fluorescent lamp not marketed as full-spectrum.**



Most claimed full-spectrum lamps are also relatively less energy-efficient. Full-spectrum T12 fluorescent lamps have an **efficacy** about 30% to 40% lower than conventional triphosphor fluorescent lamps, and thus must consume more energy to provide comparable light levels. Table 1 summarizes lamp performance data for several commercial lamp types, and includes lamp efficacy ratings.

Table 1: Performance characteristics of several popular light sources.

Light Source	CCT	CRI	FSI	Efficacy (lm/W)
<b>Equal Energy Spectrum</b>	5457	95	0	N/A
<b>Daylight</b>				
5500K	5500	100	0.35	N/A
11000K	11000	100	2.0	N/A
<b>Xenon</b>				
1000W	5900	96	1.2	22
<b>Incandescent</b>				
60-100W A-lamp	2800	100	5.3	17
60W GE Reveal A-lamp	2789	78	5.6	11
<b>Light-Emitting Diode (LED)</b>				
White LED	5000	78	5.2	13
RGB (615nm/525nm/470nm) LED mix*	4400	65	9.8	22
RGB (640nm/525nm/470nm) LED mix*	4200	26	8.2	22
<b>Compact Fluorescent</b>				
15-20W 2700-3000K	2800	82	11	61**
15-20W 5000K	5000	85	5.9	47**
15W Verilux CFS15VLX	5777	78	5.6	60**
<b>T8 Fluorescent</b>				
32W 3500K	3300	84	8.3	92
32W 5000K	4800	87	6.4	88
32W Lumiram Lumichrome 1XX	5960	93	4.7	73
32W Verilux F32T8VLX	6369	85	6.2	88
<b>T12 Fluorescent</b>				
40W 5000K	4900	91	1.8	56
40W Duro-Test Daylight 65	6588	93	1.8	53
40W Duro-Test Vita-Lite 5500	5159	88	1.4	55
40W Lumiram Lumichrome 1XC	5207	92	1.6	59
40W Verilux F40T12VLX	5833	94	1.4	53
<b>Metal Halide</b>				
320-400W / Warm color	3600	68	5.0	92
175-400W / Cool color	4300	61	4.3	90
<b>Ceramic Metal Halide</b>				
35-70W / Warm color	2900	84	6.5	79
100W / Warm color	3100	81	5.1	93
100-150W / Cool color	4100	93	1.5	90
<b>Mercury Vapor</b>				
175-400W / Coated lamp	3900	43	5.5	54
400W / Clear lamp	5900	15	9.6	53
<b>High Pressure Sodium</b>				
200-400W	2000	12	22	120
<b>Low Pressure Sodium</b>				
180W	1800	0	52	180

Light sources displayed in red are claimed as full-spectrum by their manufacturers. CCT, CRI, and FSI values for these light sources were calculated from SPD measurements performed at the Lighting Research Center; efficacy values were calculated from manufacturers' data. Entries for other sources are representative values.

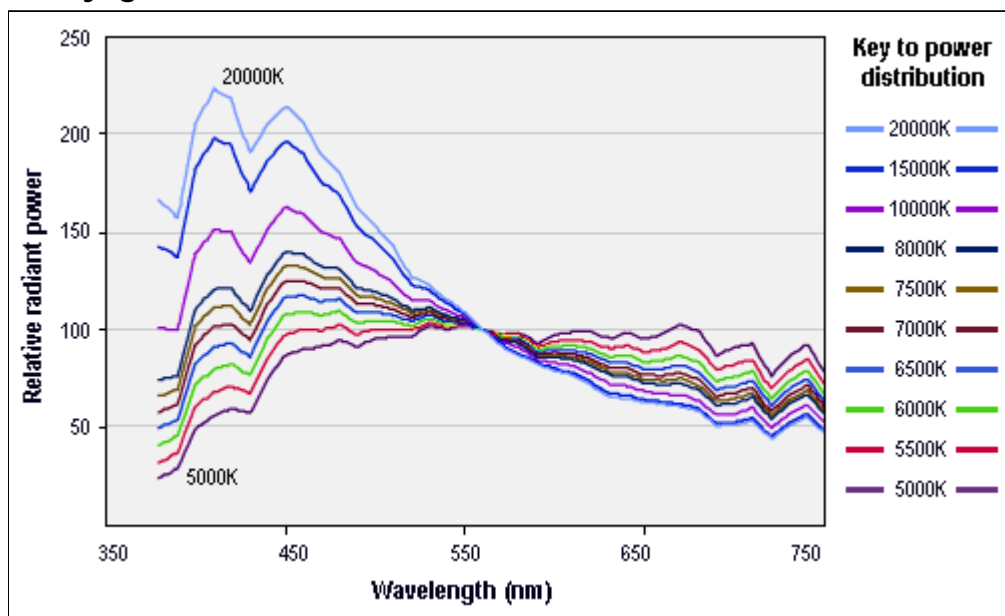
\* The values in parentheses represent the peak outputs of the respective red, green and blue LEDs mixed to create this light source.

\*\* Efficacy values for CFLs include losses from integral ballasts.

## How can full-spectrum light sources be compared?

To develop a method of comparing full-spectrum light sources, full-spectrum lighting must first be defined. Full-spectrum light sources are often claimed to mimic daylight, so it makes sense that full-spectrum light sources should be defined in terms of daylight. The problem with this approach is that there is no single **spectral power distribution (SPD)** associated with natural daylight, since the spectrum of daylight varies constantly. In Figure 4, note that the relative spectral radiant power distributions derived have a common value of 100 at the wavelength of 560 nm (CIE, 1964). Moreover, a daylight SPD is not particularly smooth and uniform depending upon atmospheric composition, particularly the amount of water vapor.

**Figure 4. Relative radiant power distribution of 10 different phases of daylight.**



The infinite variety and variance of natural daylight spectra makes it impossible to evaluate quantitatively an electric light source in terms of its ability to emulate natural daylight. Choosing a particular reference spectrum for daylight for comparison would not only be completely arbitrary, it would also undermine a basic marketing argument for manufacturers of full-spectrum light sources. Since daylight is a naturally varying light source, a light source that emulates one particular daylight spectrum is, by definition, unnatural. Nevertheless, all electric full-spectrum light sources have fixed SPDs, so it would be useful to define a reference light source to which all can be compared.

In selecting an ideal light source as a reference, an equal energy spectrum becomes the logical choice for two main reasons. First, the SPD of an equal energy spectrum is, indeed, "full" across the entire visible spectrum and, second, an equal energy spectrum is neutral with regard to any prejudicial associations, positive or negative, with "natural" light sources. Moreover, there are several electric and natural light sources that have SPDs approximating an equal energy spectrum, so choosing an equal energy spectrum as the reference full-spectrum source is not entirely abstract or irrelevant.

Formally then, the proposed reference full-spectrum light source is an ideal light source with equal energy across the visible region of the spectrum, from 380 to 730 nm, inclusive. A new metric, called full-spectrum index (FSI), based on this proposed reference, can be calculated from a light source's SPD to determine how much that SPD differs from an equal energy spectrum. FSI is based on the sums of the squared deviations (SOS) between the cumulative SPDs of the test light source and the reference equal energy source. So that spikes or dips in the SPD are weighted equally no matter where along the spectrum they occur, the SOS is calculated 351 times (one for each 1 nm increment between 380 and 730, inclusive) and the values are averaged. For each of these calculations, the starting point is incremented by 1 nm and when the end of the spectrum range is reached, it is wrapped back around to the beginning (i.e., 380 follows 730).

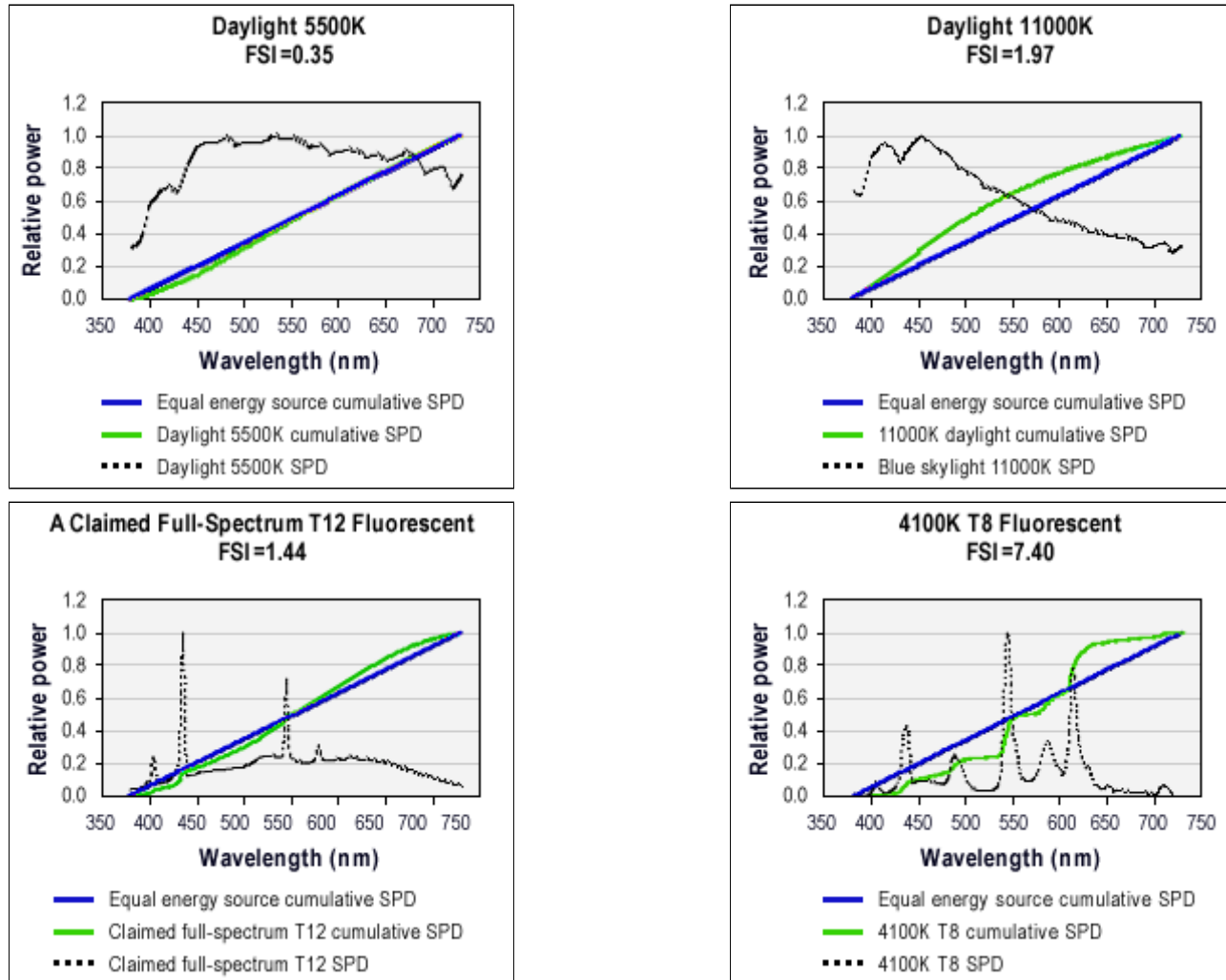
As noted in personal communication with the authors by Dr. Duane Miller of APL Engineered Materials, Inc., this averaging procedure ensures that FSI values are independent of the starting point for the calculation. The lower the FSI value the more "full" the spectrum, with zero being an equal energy spectrum. [Table 1](#) includes typical FSI ranges for several types of commercially available light sources.

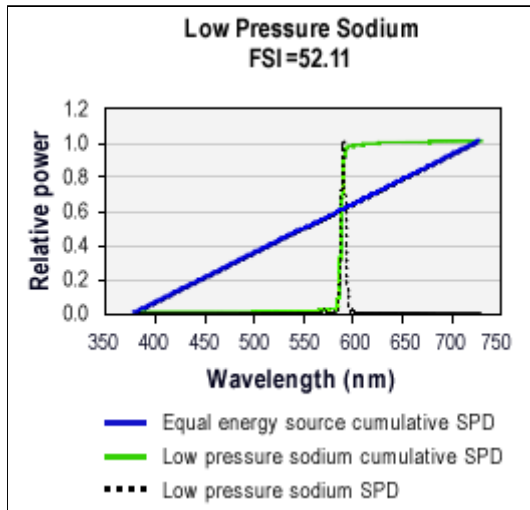
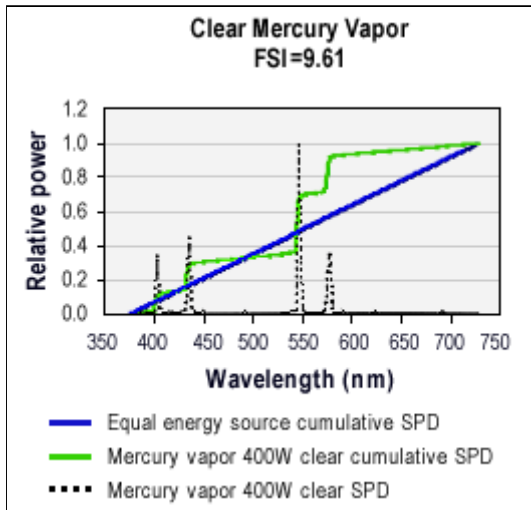
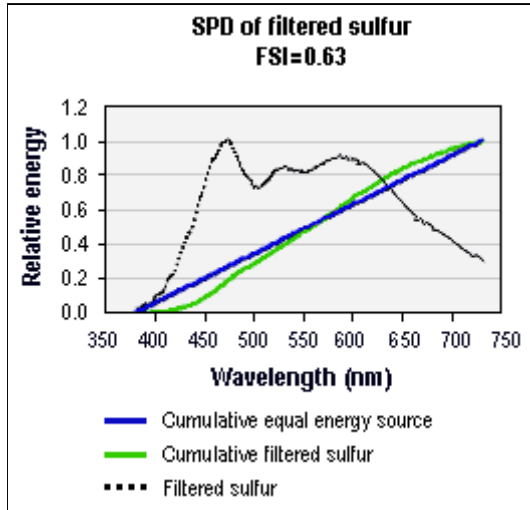
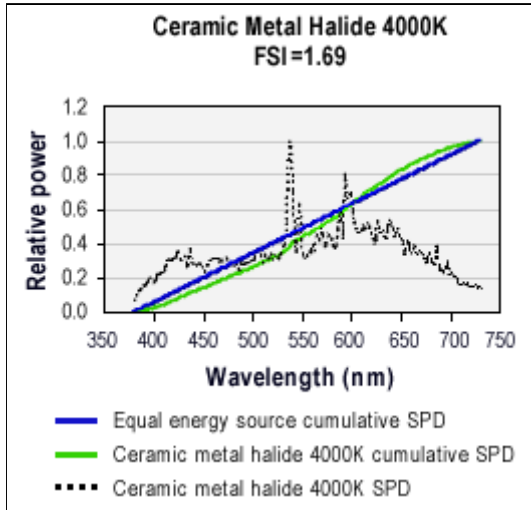
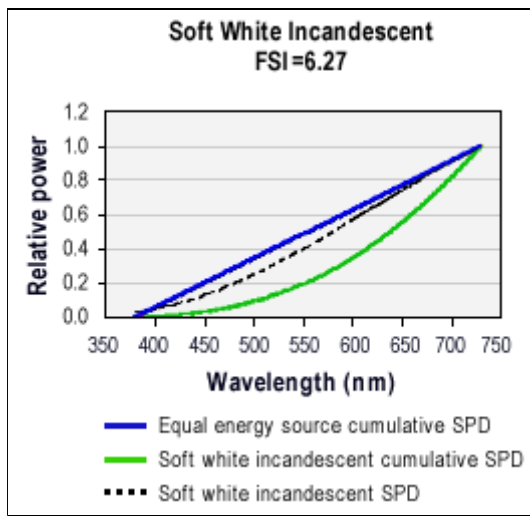
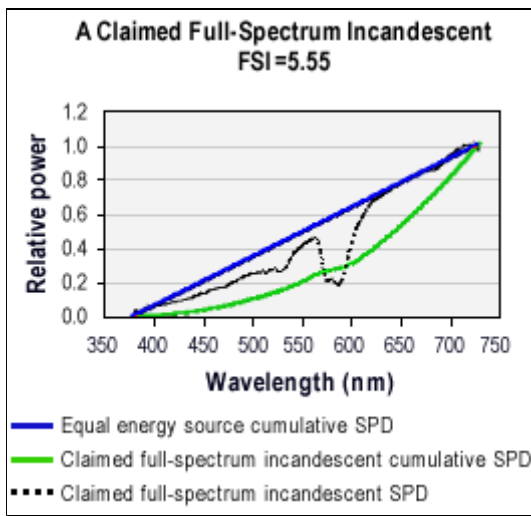
The lower limit of the FSI reference spectrum range (380 nm) was chosen because it is the shortest wavelength tabulated in the abridged International Commission on Illumination (CIE) color matching functions, and because invisible UV radiation should be excluded as part of the definition of full-spectrum light sources (see "[Is ultraviolet radiation production important?](#)"). The upper limit (730 nm) and the lower limit (380 nm) both have the same  $\bar{x}$  value of 0.0014. The upper limit, 730 nm, minimizes the influence of invisible infrared radiation on the FSI calculations while still including the important contributions of long-wavelength radiation on color perception. As an important note, choosing a slightly different spectral range for the reference full-spectrum light source, shorter or longer, does not significantly alter the relative FSI values for the commercially available light sources shown in [Table 1](#). Figure 5 presents the spectra of several popular light sources together with their cumulative SPDs. These figures illustrate the concept behind FSI, namely, the more the cumulative SPD resembles the flat slope of a cumulative equal energy spectrum, the closer the light source is to having a "full" spectrum.

Based on an arbitrary cutoff of  $FSI = 2.0$ , the following light sources can be categorized as full-spectrum: natural daylight from 4000K to 11000K, xenon lamps, some fluorescent T12 lamps marketed as full-spectrum, some T12 fluorescent lamps not marketed as full-spectrum, and some ceramic metal halide lamps. At the time this report was written, the following T12 lamps marketed as full-spectrum met the  $FSI = 2.0$  cutoff: Duro-Test Daylight 65, Duro-Test Vita-Lite 5500K, Lumiram Lumichrome 1XC, and Verilux VLX fluorescent lamps.

**Figure 5. Relative cumulative SPDs for two phases of daylight and several electric light sources.**

The cumulative SPD for an equal energy spectrum is shown (blue) with the cumulative SPD of the example light source (green). The FSI values in these figures are for specific lamp SPDs and are not necessarily the same as the representative values in [Table 1](#).





## Appendix: Calculating Full-Spectrum Index

```
% fifth, calculate the FSI (full spectrum index)
% interpolate SPD from 380nm to 730nm with 1nm internal
t=380:1:730;
spd=interp1(wavelength_spd,spd,t,'spline');
spd(isnan(spd)) = 0.0;
spd=spd/max(spd);

% Equal energy accumulative spd
EEspd=(1/351:1/351:1);

% circular calculation of FSI
for j=1:351
    for i=1:351
        cum(i,:)=sum(spd(1:i,:),1)./sum(spd,1);
        leastwo(i,:)=(cum(i,:)-EEspd(i)).^2;
    end
    sumleastwo(j,:)=sum(leastwo,1);
    spd=circshift(spd,1);
end
meanleastwo=mean(sumleastwo,1);
FSI=100-4*meanleastwo;
```

## Resources

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### Additional Internet resources

Duro-Test Lighting, Inc.	<a href="http://www.durotest.com">http://www.durotest.com</a>
Environmental Lighting Concepts, Inc.	<a href="http://www.ott-lite.com">http://www.ott-lite.com</a>
GE Lighting	<a href="http://www.gelightnet.com/nacwc/naenglish.html">http://www.gelightnet.com/nacwc/naenglish.html</a>
Institute for Research in Construction	<a href="http://www.irc.nrc-cnrc.gc.ca/fulltext/ir659/contents.html">http://www.irc.nrc-cnrc.gc.ca/fulltext/ir659/contents.html</a>
Institute for Research in Construction	<a href="http://www.irc.nrc-cnrc.gc.ca/ie/light/spectrum.html">http://www.irc.nrc-cnrc.gc.ca/ie/light/spectrum.html</a>
Lumiram Electric Corp.	<a href="http://www.lumiram.com">http://www.lumiram.com</a>
OSRAM SYLVANIA	<a href="http://www.sylvania.com/home_us.htm">http://www.sylvania.com/home_us.htm</a>
Philips Lighting Co.	<a href="http://www.lighting.philips.com/nam/index.php">http://www.lighting.philips.com/nam/index.php</a>
Verilux, Inc.	<a href="http://www.verilux.net">http://www.verilux.net</a>
Verilux: The Healthy Light Catalog	<a href="http://www.healthylight.com/bulb3.html">http://www.healthylight.com/bulb3.html</a>

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**Spectral power distribution (SPD)**

A representation of the radiant power emitted by a light source as a function of wavelength.

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**x-bar**

Color matching function  $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$  are used to define the color-matching properties of the CIE 1931 standard observer. In 1931, CIE defined the color-matching functions  $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$  in the wavelength range from 380nm to 780 nm at wavelength intervals of 5nm.

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**Duration of full-spectrum lighting exposure necessary to affect vitamin D levels**

According to Holick, exposure to 1.5 minimal erythema doses (MED) of UVB will produce pronounced transient increases in serum vitamin D concentrations in Caucasians (Holick, 1985). One manufacturer defines their full-spectrum fluorescent lamp's UVB radiation amount as  $15 \pm 4$  W/lumen (Veitch, 1994). For office lighting, the illuminance on occupants' hands and face is between 300 lux to 1000 lux. The area of an adult's two hands and face exposed to the UVB radiation can be estimated to be about 0.2 square meters. So, the total lumens projected to the skin can be calculated as between 60 to 200 lumens. The total amount of UVB exposure will then be equal to:

**Upper limit:**

$$\text{Total UVB amount, } 19\mu\text{W/lumen} \times 200 \text{ lumens} = 0.0038\text{W}$$

$$\text{UVB intensity, } 0.0038\text{W} / 0.2 \text{ square meters} = 0.019\text{W/m}^2$$

**Lower limit:**

$$\text{Total UVB amount, } 11 \text{ W/lumen} \times 60 \text{ lumens} = 0.00066\text{W}$$

$$\text{UVB intensity, } 0.00066\text{W} / 0.2 \text{ square meters} = 0.0033\text{W/m}^2$$

According to Thorington, exposure under sunlight for 15 minutes with UVB intensity at  $1.54\text{W/m}^2$  will yield one MED (Thorington, 1985). Therefore,

$$1 \text{ MED} = 1.54\text{W/m}^2 \times 15 \text{ minutes} \times 60 \text{ seconds} = 1386 \text{ joules/m}^2$$

To yield 1.5 MED under the above defined full-spectrum lamps, the exposure time should be:

**Maximum:**

$$1386 \text{ J/m}^2 \times 1.5 / 0.0033\text{W/m}^2 = 175 \text{ hours}$$

**Minimum:**

$$1386 \text{ J/m}^2 \times 1.5 / 0.019\text{W/m}^2 = 30.4 \text{ ours}$$

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